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Ralph A./Bradley, Sushil S./Srivastava ~~&~~ Adolf/Lanzdorf

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PREFACE

The main body of this technical report is an article prepared for a special issue of *Communications in Statistics, Part A* on statistics in weather modification. It will be preprinted also in the *Proceedings of the Workshop on Statistical Design and Analysis of Weather Modification Experiments*, Tallahassee, October, 1978, with permission of the Editor. Inclusion of the article as part of this technical report maintains continuity of reporting under the contract.

The article is based partly on our ONR Technical Report No. 133, FSU Statistics Report No. M467. Attention is directed also to our January 31, 1979 Errata to that technical report, with those corrections included in the article. Section 5 of the article refers to research by Elton Scott and details were given in ONR Technical Report No. 127, FSU Statistics Report No. M442. A follow-on report by Scott is in preparation. Sections 4 and 6 of the article contain some new analyses with transformed data and some comments on other analyses not shown. A Supplementary Appendix, at the end of this report, shows results of these additional analyses not reported previously.

A complete list of technical reports on this contract is appended.

Ralph A. Bradley

SOME APPROACHES TO STATISTICAL ANALYSIS OF A WEATHER MODIFICATION EXPERIMENT

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ABSTRACT

Data from a weather modification experiment are examined and a number of statistical analyses reported. The validity of earlier inferences is studied as are the utilities of various statistical methods. The experiment is described. The original analysis of North American Weather Consultants, who conducted the experiment, is reviewed. Data summarization is reported. A major approach to analysis is through the use of cloud-physics covariates in regression analyses. Finally, a multivariate analysis is discussed. It appears that the covariates may have been affected by treatment (cloud seeding) and that their use is invalid, not only reducing error variances but removing treatment effect. Some recommendations for improved design of similar future experiments are given in a concluding section, including preliminary trial use of blocking by storms.

1. INTRODUCTION

Phase I of the Santa Barbara Convective Seeding Test Program was conducted by North American Weather Consultants (NAWC) from 1967 through 1971 for the Research Department, Naval Weapons Center, China Lake, California. A concurrent study on the large-scale effects of cloud seeding was undertaken for the Bureau of Reclamation, U.S. Department of the Interior, Denver, Colorado by Aerometric Research Inc., the research affiliate of NAWC. Research on the design and analysis of weather modification experiments at the Florida State University is sponsored by the Office of Naval Research, Department of the Navy, Washington, D.C. Data from the Phase I Santa Barbara experiment, provided through the courtesy of NAWC, have been used for trial analyses. Some approaches to statistical analysis of the Phase I data are reported in this article.

A brief summary of the Phase I experiment follows. More detail is given in technical reports by Elliott and Thompson (1968a, 1968b, 1969, 1972) and in publications by Elliott, St. Amand, and Thompson (1971) and Brown, Elliott, Thompson, St. Amand and Elliott (1974). Two final reports were issued, one for the Naval Weapons Center and one for the Bureau of Reclamation, by Thompson, Brown and Elliott (1975) and Brown, Thompson and Elliott (1975) respectively. Both final reports include Phase II experiment results, 1971 through 1974. In this article, attention is on Phase I data because of experimental design changes and the introduction of aerial seeding in Phase II. Data collected for the Bureau of Reclamation study is used unless otherwise specified because of its augmented network of raingages.

Winter storms in the Santa Barbara region have identifiable convective cells grouped into bands, usually taking from one-half to one and one-half hours to pass over a point. Several convective bands may occur in a storm or it may be a single frontal band. The convective band was used as the experimental unit in the Phase I experiment. Criteria for the "seedability" of a

convective band were established; in operation, they reduced to a wind flow requirement such that the possible effects of seeding would fall mainly in a target area and the expectation of substantail precipitation. Band detection was either by radar, confirmed through precipitation at a telemetered raingage in a control area to the west of a single ground seeding site, or through precipitation at two such telemetered raingages. A predetermined randomized decision to seed or not seed an experimental unit, a seedable convective band, was applied. Figure 1, taken from Elliott, St. Amand and Thompson (1971), depicts the general experimental set up; not all raingages used are shown nor were all raingages always in operation. Seeding in Phase I was ground based from a mountain crest at 1065m. above sea level indicated in Figure 1. High output, silver-iodide, pyrotechnic devices, ignited at 15 minute intervals from the beginning of band passage for seeded bands, were used.

Band precipitation data were obtained for all raingages in control and target areas operable for a band. (The number of raingages was increased from time to time during the Phase I experimentation.) The procedure included:

(i) tracking of the precipitation band pattern across the gage network on the basis of plots of available precipitation and radar information,

(ii) determination of the time of band passage (and hence time of band duration) at each raingage, and

(iii) calculation of total precipitation from the raingage record attributable to the band.

To avoid subconscious bias, the meteorological analyst determining raingage band passage times and precipitations was uninformed as to which bands were seeded. Considerable skill was required from the analyst. A major source of variation may arise from these determinations, a disadvantage in the use of convective bands as experimental units, perhaps offset by the resulting increase in the number of experimental units available in a season.

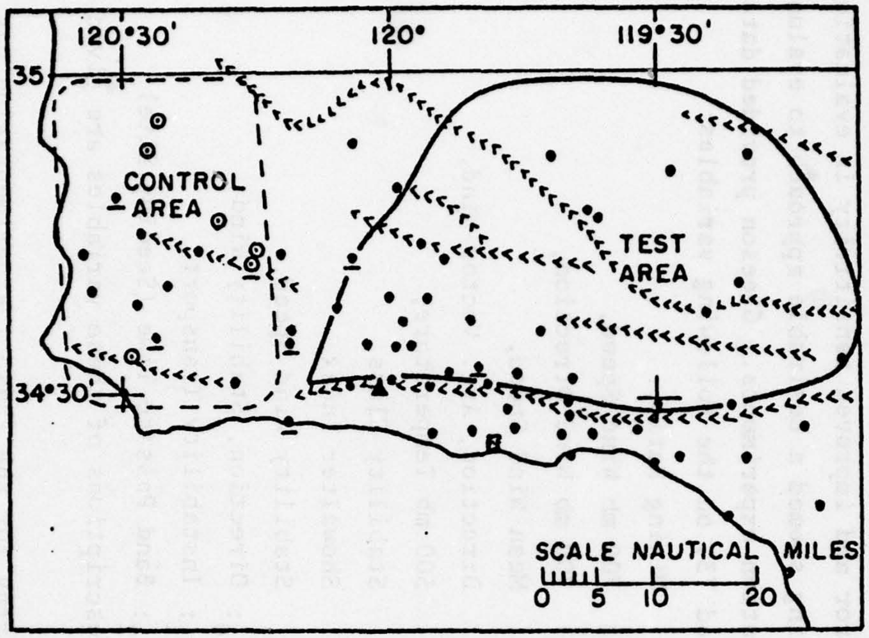

FIG. 1. Santa Barbara Pyrotechnic Seeding and Control Test Areas. Source: Figure 2, Elliott, St. Amand, and Thompson (1971). Raingage sites are designated by solid or open circles, telemetered gages underlined. The seeding and radar site is indicated by a solid triangle.

Air mass characteristics of each band were determined from radiosonde observations at Santa Barbara Airport and Vandenberg Air Force Base (VBG in Figure 1). An attempt was always made to obtain a sounding as a band passed over the airport. Gleeson (1977) summarized the meteorological data with a view to their use as covariates. The use of covariate analysis for the reduction of experimental error and improved sensitivity in evaluations of the effects of seeding seemed a desirable approach to evaluation of weather modification experiments. Gleeson provided data for each band (except Band 73) on the following variables:

$$
\begin{aligned}
&X_1: \text{ Mixing Ratio,}\\
&X_2: \text{ 700 mb Wind Speed,}\\
&X_3: \text{ 700 mb Wind Direction,}\\
&X_4: \text{ Mean Wind Speed,}\\
&X_5: \text{ Direction, Avg. Vector Wind,}\\
&X_6: \text{ 500 mb Temperature,}\\
&X_7: \text{ Stability Class,}\\
&X_8: \text{ Showalter Index,}\\
&X_9: \text{ Stability Wind Speed,}\\
&X_{10}: \text{ Direction, Stability Wind,}\\
&X_{11}: \text{ Instability Transport,}\\
&X_{12}: \text{ Band Passage Time (Seeding Site).}
\end{aligned}
\qquad (1.1)
$$

More detailed descriptions of these variables are given by Gleeson.

The data array for the Phase I experimentation may be viewed as a data matrix with N rows or bands, the first N_1 rows for unseeded bands and the second N_2 rows for seeded bands, $N = 107$, $N_1 = 51$, $N_2 = 56$, and with columns containing precipitation responses at individual raingages, possibly grouped by locations, and values of the concomitant variables, X_1 to X_{12}. The data are not without problems. Raingage precipitation responses are correlated (correlation approximately 0.6) as would be expected. There are missing data for many gages. There may be problems also in consideration of rows as independent observation vectors.

Elliott and Thompson (1968b) consider the persistence effects of seeding and conclude: "some seeding precipitation enhancement may have occurred in non-seeded bands which follow on seeded bands". NAWC analyses, Elliott and Thompson (1969), suggest the possibility of an up-wind effect west of the seeding site attributable not to westward seeding contamination but to seeding-caused blocking of the air-mass flow leading to up-wind convection development. Bradley, Srivastava and Lanzdorf (1977a) provide precipitation summarization data used below. These data, together with those of Gleeson, are available to readers interested in investigating other approaches to the analysis of this weather modification experiment.

Primary NAWC analyses are reviewed in the next section. This is followed by a short discussion of the authors' efforts to summarize the precipitation data. The use of the available data in regression-covariance analyses is reported, followed by a preliminary multivariate analysis. The article concludes with some remarks on the design of similar, future weather modification experiments.

2. NAWC DATA ANALYSIS

The main NAWC approach to data analysis was on a raingage station-by-station basis.

Let $y_{i\alpha}$ denote precipitation at station i from band α, $\alpha = 1,\ldots,N$. Let $\gamma_\alpha(i) = 1$ or 0 as station i was operative or not operative for band α and let $\delta_\alpha(i) = 1$ or 0 as band α was seeded or not seeded. Then $\sum_\alpha \gamma_\alpha(i) = N(i)$ and $\sum_\alpha \delta_\alpha(i)\gamma_\alpha(i) = N_s(i)$, respectively the number of observations and the number of seeded bands recorded at station i. The number of unseeded bands at station i is $N_{ns}(i) = N(i) - N_s(i)$. Then

$$\overline{T}_s(i) = \sum_\alpha \delta_\alpha(i)\gamma_\alpha(i)y_{i\alpha}/N_s(i) \tag{2.1}$$

and

$$\overline{T}_{ns}(i) = \sum_\alpha [1-\delta_\alpha(i)]\gamma_\alpha(i)y_{i\alpha}/N_{ns}(i) \tag{2.2}$$

are precipitation averages at station i for seeded and non-seeded bands respectively. Six control area detection stations were used, stations circled in Figure 1. If k indexes these control stations, define

$$\overline{C}_s = \sum_k \overline{T}_s(k)/6 \qquad (2.3)$$

and

$$\overline{C}_{ns} = \sum_k \overline{T}_{ns}(k)/6. \qquad (2.4)$$

The descriptive statistic used by NAWC for station i, a double ratio, is

$$DR(i) = [\overline{T}_s(i)/\overline{C}_s]/[\overline{T}_{ns}(i)/\overline{C}_{ns}]. \qquad (2.5)$$

Use of the double ratio was compared with use of the single ratio,

$$SR(i) = \overline{T}_s(i)/\overline{T}_{ns}(i). \qquad (2.6)$$

It was found that much the same results were obtained for the two statistics. The intent in use of (2.5) was to standardize the comparison of seeded and non-seeded responses through divisions by control area precipitations, assumed to be unaffected by seeding. The control area detection stations had only a few missing observations and apparently $\overline{C}_s$ and $\overline{C}_{ns}$ in (2.3) and (2.4) were then evaluated from the available observations.

Figure 2, based on the Naval Weapons Center study, shows contours for the double ratio of (2.5) for the Phase I experiment. Similar figures are given by Elliott and Thompson (1972) for the single ratios of (2.6) and for subdivisions of the data by years, stability classes, and 500 mb temperatures. The locations of regions of possible precipitation enhancement are fairly stable in all such figures and they tend to be regions with low average precipitations for both seeded and unseeded bands.

NAWC states in their various reports that the Wilcoxon-Mann-Whitney, two-sample, rank test was used to assess the significance of double and single ratios for each raingage station. ~~Significances were noted as in Figure 2~~. The methods of application of the test are not clear in the reports but we give our understandings. For the single ratio, $y_{i\alpha}$ was used; the precipitation

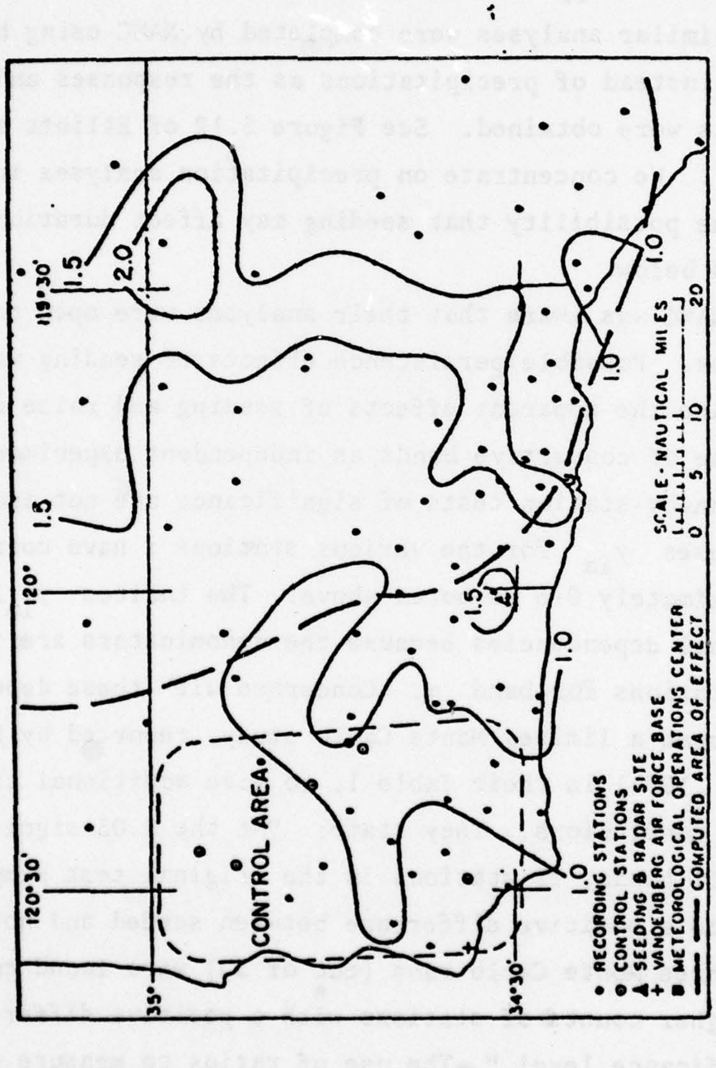

FIG. 2. Composite Double Ratios of Precipitation for 1967-71, All Bands. Ground-Seeded 56 Seeded and 51 Not Seeded. Source: Figure 5.2, Elliott and Thompson (1972).

measurements themselves were grouped into two samples, seeded and unseeded, and the rank test applied. For the double ratio, $y_{i\alpha}/\overline{C}_{\alpha}$ was calculated for each band α at stations i, $\overline{C}_{\alpha}$ being the average of the six (or available) control-area, detection stations for band α, and these indices were grouped into two samples as before and the test applied for station i.

Similar analyses were completed by NAWC using band duration times instead of precipitations as the responses and very similar results were obtained. See Figure 5.12 of Elliott and Thompson (1972). We concentrate on precipitation analyses in this article, but the possibility that seeding may affect duration time is discussed below.

NAWC was aware that their analyses were open to possible criticisms. Possible persistence effects of seeding would seem to decrease the apparent effects of seeding and raise questions about the use of convective bands as independent experimental units. Station-by-station tests of significance are not independent. The responses $y_{i\alpha}$ for the various stations i have correlations of approximately 0.6 as noted above. The indices $y_{i\alpha}/\overline{C}_{\alpha}$ have additional dependencies because the denominators are the same for all stations for band α. Concerned with these dependencies, NAWC conducted a limited Monte Carlo study, reported by Elliott and Brown (1971) in their Table 1, to give additional credence to their concludions. They state: "At the 0.05 significance level for all bands, 29 stations in the original test sample were found to show a positive difference between seeded and not-seeded cases; and three Monte Carlo runs (out of 50) were found to have as high or higher counts of stations with a positive difference at this significance level." The use of ratios to measure precipitation enhancement is open to question depending on project objectives. If large ratios occur in areas of relatively low precipitation, somewhat sparsely represented by raingages, the effect on total or average precipitation for a larger defined target area may be small and the result of little economic value.

3. DATA SUMMARIZATION

A more direct approach to the analysis of a weather modification experiment is to consider summary measures of precipitation for each experimental unit over designated response areas. The arithmetic mean of the raingage measurements over a response area for each unit would be the summary measure typically used.

Bradley, Srivastava and Lanzdorf (1977a,b) defined response areas as in Table I. The locations of these areas may be identified through reference to Figure 2. The first five

TABLE I

Definitions of Response Areas

Response Area	Ranges in Degrees Latitude	Ranges in Degrees Longitude	Number of Stations
(i)	34.0-35.25	118.0-120.02	107
(ii)	34.4-35.0	119.51-120.02	26
(iii)	34.0-35.0	118.0-119.51	72
(iv)	Areas (ii) + (iii)		98
(v)	All Stations in the Naval Weapons Center Reports East of Seeding Site, long. 120.02		61
Control*	34.4-35.25	120.02-120.60	34

*The Control Area for the Naval Weapons Center study consists of all 39 stations west of the seeding site.

areas will be referenced as Target Areas and the last as the Control Area. The number of raingage stations and the data used for Target Areas (i)-(iv) are those of the Bureau of Reclamation study and those for Target Area (v) are those of the Naval Weapons Center study with minor modifications noted in the two cited references. Note that these target areas cover the test area of Figure 1, but

that some raingages existed outside of these response areas, some of them in arid regions.

Precipitation averages in inches are exhibited in Table II for the various response areas. They were computed as simple averages of the individual convective band averages of available raingage measurements for the band in the designated response area. The numbers of raingages available increased

TABLE II

Precipitation Means in Inches

Response Areas	(i)	(ii)	(iii)	(iv)	(v)	Control
Seeded Bands	0.257	0.329	0.249	0.271	0.267	0.234
Unseeded Bands	0.178	0.229	0.172	0.187	0.190	0.203

somewhat with the seasons and not all raingages were operable for all convective bands. Table II is intended only to indicate the nature of responses. It reinforces impressions given by Figure 2 with its double ratios. The Control Area mean for seeded bands is higher than that for unseeded bands, as are Target Area means, suggesting either that seeding had some effect in the Control Area or misfortune in the randomized choices of bands to be seeded.

With the intent of improvement of data summarization, Bradley, Srivastava and Lanzdorf (1977a,b) summarized the precipitation data through the use of response surfaces for the Control Area and Target Area (i) separately. The basic independent variables were the coordinates of latitude and longitude for the raingage stations with individual, raingage precipitation measurements as the

dependent variable observations. Separate response surfaces were found for each convective band. It was found necessary to use general cubic response models to represent responses adequately. Precipitation volumes and their variances were calculated, the volumes obtained through integrations of the surfaces over the designated target areas or control area. Figure 3 is typical of results obtained; the region where the surface is negative is offshore.

The response surface approach was successful as a method of data summarization. It was not successful in improvement of data summarization in comparison with use of the raingage means over stations within response areas for a convective band. Some 70% of the inherent variation in responses among raingages within a band and response area was explained by the independent variables, the percentages varying considerably from band to band. Residuals from fitted surfaces exhibited only limited spatial trends when the cubic surfaces were used. Correlations between precipitation volumes calculated from the response surfaces and precipitation means were given by Bradley, Srivastava and Lanzdorf (1977a,b). They ranged from 0.97 to 0.99 for Target Areas (i)-(iv) and the correlation was 0.89 for the Control Area. The use of volumes in consideration of the effects of seeding cannot be expected to yield additional insights, although Bradley, Srivastava and Lanzdorf (1978) did examine their use as reported in the next section.

Scott (1978) used a multivariate approach to data summarization. He found principal components among raingage responses in both Target Area (i) and the Control Area with a view to summarizing responses through one or more orthogonal linear combinations of the raingage measurements of stations in response areas for each band. Thus, raingage responses were treated as variates and convective bands as experimental units. Substantial pruning of the data and some innovations were required to circumvent the serious problems of missing observations in multivariate analysis.

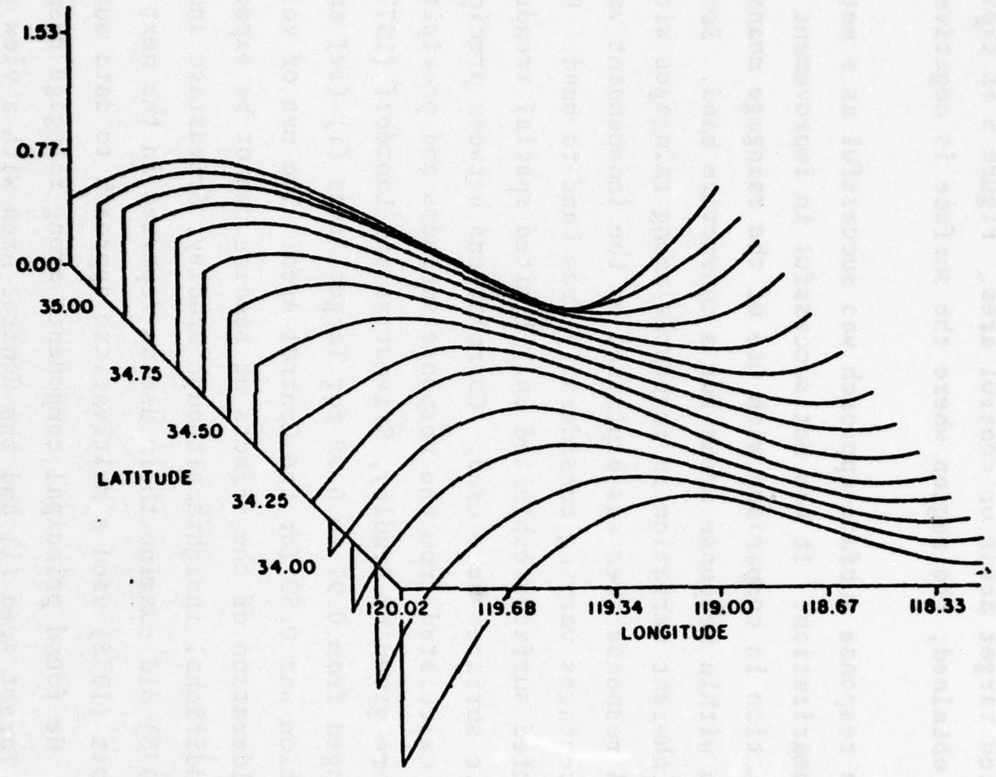

FIG. 3. Graph of Cubic Response Surface: Band 96 (Seeded), Target Area (i). Source: Figure 2, Bradley, Srivastava, and Lanzdorf (1977b). Vertical axis is 2.3 times precipitation in inches.

Correlation matrices were obtained and principal components determined, along with their eigenvalues. The first three principal components were interpretable approximately as a mean response, a coastal versus inland contrast, and an East-West contrast. Percentages of variation explained by these components were respectively 71.3, 6.7 and 5.9 in Target Area (i) and 76.1, 6.7 and 4.7 in the Control Area. The correlations of the first component with the band mean were 0.997 for Target Area (i) and 0.985 for the Control Area. Scott is engaged in use of these results in examination of the effects of seeding. The first component cannot be expected to yield new insights; other components may add some new information.

4. COVARIANCE ANALYSES

Weather modification experiments are conducted necessarily in a natural environment involving much variability. The use of covariates in analyses for the reduction of experimental error appears to be the major available means to improved experimental design. It was for this purpose that Gleeson (1977) summarized information on covariates as discussed in Section 1. We report in this section on covariance analyses effected through use of multiple regression methods.

Bradley, Srivastava and Lanzdorf (1978) reported on initial covariance analyses. (Some later analyses are reported below.) Regression models used were of the form,

$$U = \beta_0 + \sum_{i=1}^{p} \beta_i V_i + \delta Z + \varepsilon, \tag{4.1}$$

where U is a precipitation response variable for a target area, V_i is the i^{th} covariate, $Z = 1$ or 0 as the experimental unit was or was not seeded, the β's and δ are regression parameters, and ε is a random error. The data matrix has rows, $(U_\alpha, V_{1\alpha}, \ldots, V_{p\alpha}, Z_\alpha)$, $\alpha = 1, \ldots, N$. The regression parameters were estimated by weighted least squares through minimization of

$$\sum_{\alpha=1}^{N} w_\alpha (U_\alpha - \beta_0 - \sum_{i=1}^{p} \beta_i V_{i\alpha} - \delta Z_\alpha)^2. \quad (4.2)$$

In the referenced report, use of the set of covariates of (1.1) and their interactions with treatment (seeding), along with X_c, a measure of Control Area precipitation, was explored. Both target area mean precipitation and target area precipitation volume, see Section 3, were used as U for Target Areas (i)-(iv), together with corresponding measures for X_c. No results are summarized here for precipitation volumes since they were very similar to those for mean precipitations. Pairwise unweighted correlation coefficients are shown in Table A-I for mean precipitation, X_c, and the covariates of (1.1) to give an indication of relationships for Target Area (i). Note that X_c, Control Area mean precipitation, and X_{12}, Band Passage Time, correlate most highly with target area mean precipitation; both of these covariates may be affected by seeding -- we have noted a possible effect of seeding up-wind from the seeding site in the Control Area and it has been conjectured that the effect of seeding may be to increase rainfall through an increase in band passage time.

It was reported in the reference, after preliminary analyses, that seven of the twelve covariates of (1.1) were sufficient for experimental error reduction. They were:

X_2: 700 mb Wind Speed,
X_3: 700 mb Wind Direction,
X_6: 500 mb Temperature,
X_7: Stability Class, (4.3)
X_8: Showalter Index,
X_{11}: Instability Transport,
X_{12}: Duration of Band Passage.

The selection was based on redundancy considerations and their contributions to error reduction. Final analyses were done for four models with unit weights (unweighted) and weights, $w_\alpha = n_\alpha / s_\alpha^2$, where n_α is the number of raingage observations

contributing to the precipitation mean for band α and s_α^2 is the variance among those observations. The models in the form (4.1) had the covariates V_i as follows:

Model	Identification of $V_1,\ldots,V_p$
(1)	$X_2, X_3, X_6, X_7, X_8, X_{11}, X_{12}$.
(2)	V's of Model (1) plus $X_2Z, X_3Z, X_6Z, X_7Z, X_8Z, X_{11}Z, X_{12}Z$.
(3)	X_c plus V's of Model (1).
(4)	X_c plus V's of Model (2).

(4.4)

Values of the coefficient of determination R^2, the square of the multiple correlation coefficient for $N = 106$ bands*, are given for the four models and Target Areas (i)-(v) in Table III.

TABLE III

Coefficients of Determination (R^2) for Regressions with Precipitation Means

Target Area	Models Without Control Mean				Models With Control Mean			
	Unweighted		Weighted**		Unweighted		Weighted**	
	(1)	(2)	(1)	(2)	(3)	(4)	(3)	(4)
(i)	0.597	0.621	0.364	0.437	0.712	0.750	0.593	0.615
(ii)	0.578	0.608	0.373	0.457	0.789	0.815	0.681	0.691
(iii)	0.578	0.606	0.285	0.468	0.646	0.691	0.505	0.582
(iv)	0.604	0.629	0.371	0.442	0.712	0.751	0.589	0.610
(v)	0.575	0.593	0.344	0.426	0.778	0.805	0.603	0.627

**See Table A-5, Bradley, Srivastava and Lanzdorf (1978). Values of R^2 in the reference for weighted regressions have been corrected.

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*See Gleeson (1977); there were 107 bands but covariate data were missing for Band 73.

Bradley, Srivastava and Lanzdorf (1978) gave estimates of the regression parameters and corresponding analysis of variance tables with sources of variation being reduction in variation due to basic covariates, additional reductions due to interactions (when included in the model) of the basic covariates with seeding, final reduction due to seeding, and residual variation. Results were disappointing. There were no apparent effects due to seeding. There was little interaction. The combined effects of the basic covariates were significant, generally at the 0.01 level of significance.

We were not satisfied with the preliminary analyses. Standard deviations were related to means as seen in Figure 4 below for Target Area (i). Values of n_α varied also. The weighted analyses gave very heavy weights to bands with low precipitation means; values of R^2 were reduced as seen in Table III and weighted means were quite different from the unweighted means of Table II, often suggesting more precipitation for unseeded bands. We report now on new analyses with the data transformed to stabilize variances.

Analysis of the data of Figure 4 and similar data for the other target areas suggested the use of logarithmic transformations to stabilize variances. Given a raingage observation y, the transformed responses were of the form, log (1+ay). Correlations with U_2, the target area mean of the transformed responses, are shown in Table A-I for Target Area (i); they are very close to those for U_1, the target area mean precipitation. Figure 5 shows the standard deviations of the transformed responses plotted against values of U_2 for Target Area (i). It is seen that variances have been stabilized except for small values of U_2,

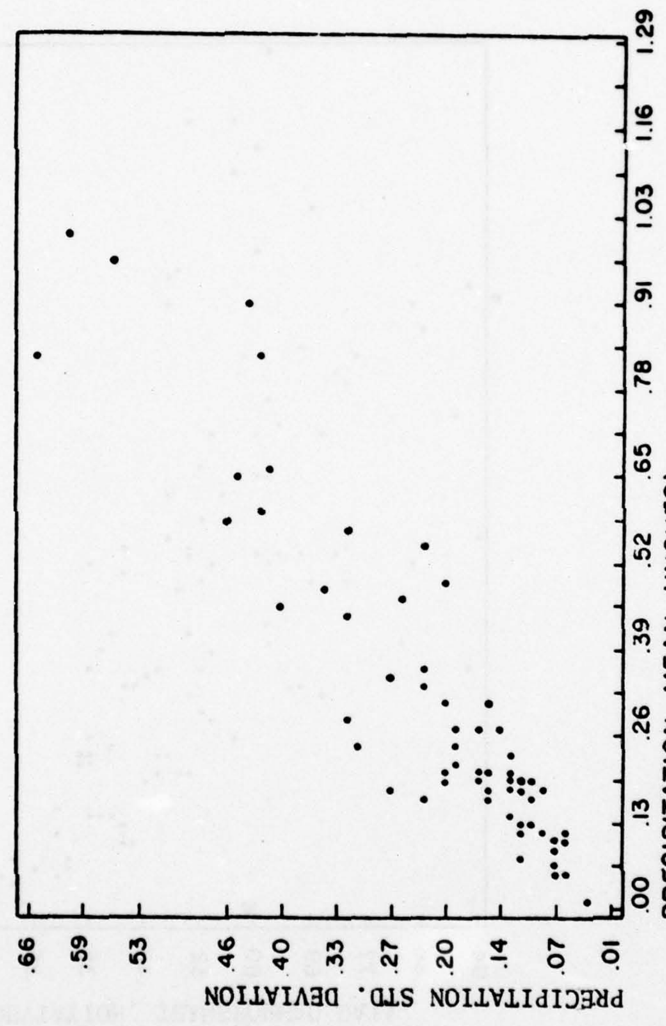

FIG. 4. The Relationship between Mean and Standard Deviation, Target Area (i).

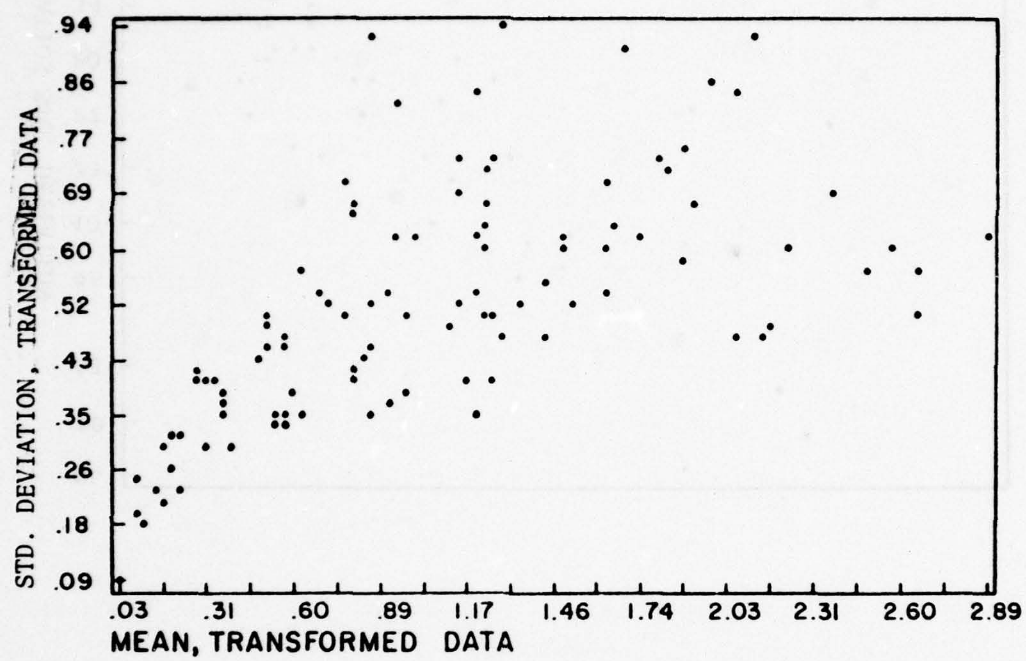

FIG. 5. The Relationship between Mean and Standard Deviation; Transformed Data, Target Area (i).

values for convective bands that may not have been acceptable "seedable" bands.

Regression analyses similar to those described above were done. Models with and without X_c and X_{12} were used because it had been suggested that they may have been affected by seeding. The response variable for each model is the mean of the transformed precipitations noted above for the designated target area and band. The weights w_α in (4.1) were taken to be n_α, the number of raingages operative in the target area for band α. The models used were as follows:

Model	Identification of $V_1,\ldots,V_p$
(5)	$X_c, X_2, X_3, X_6, X_7, X_8, X_{11}, X_{12}$.
(6)	Model (5) less X_c.
(7)	Model (5) less X_{12}.
(8)	Model (5) less X_c, X_{12}.
(9)	Model (5) plus $X_2Z, X_3Z, X_6Z, X_7Z, X_8Z, X_{11}Z, X_{12}Z$.

(4.5)

Results from these newer regression analyses are summarized. Table IV shows values of R^2 that may be compared with those of Table III. In particular, values for models (5) and (6) of Table IV may be compared respectively with those for models (3) and (1)

TABLE IV

Coefficients of Determination (R^2) for Regressions with Means of Transformed Precipitations

Target Area	Models (5)	(6)	(7)	(8)	(9)
(i)	0.720	0.616	0.659	0.293	0.748
(ii)	0.769	0.577	0.732	0.236	0.788
(iii)	0.663	0.603	0.585	0.299	0.696
(iv)	0.725	0.632	0.657	0.302	0.752
(v)	0.741	0.558	0.709	0.229	0.764

of Table III. Slightly larger values of R^2 were obtained with the transformed data. Results for model (8) show that R^2 is reduced considerably when X_c and X_{12} are omitted as covariates. Model (9) has values of R^2 similar to but slightly larger than for Model (5). Table A-II contains the essentials of analysis of variance tables for models (5)-(9) for the five target areas of Table I based on the transformed data. It is seen that use of X_{12}, Duration of Band Passage and X_c, Control Area mean precipitation, to a lesser extent, as covariates reduces the apparent effect of seeding; F-ratios for Seeding are largest for model (8) without inclusion of either X_c or X_{12}. Regression coefficients for model (5) are given in Table A-III for all five target areas. These values permit reconstruction of the estimated regression models and reinforce comments relative to X_c and X_{12} above. Examination of residuals about estimated regression models for the transformed data suggests that transformation improved symmetry and approximate normality of their distributions.

Gleeson (1977) saw no major differences between results on covariates for seeded and unseeded bands but he did observe that the differences exhibited some consistency. After some discussion, he wrote: "Taken separately the effect of these differences may be insignificant, but in combination they suggest that the total precipitation that might have been realized from seeded bands, had they not been seeded, would have been larger than the total amount that fell from nonseeded bands." Gleeson's concern could be explained by unfortunate randomization in the seeding decision or through a seeding effect on the covariates. We are inclined to the latter possibility. We have referred to Elliott and Thompson (1969), who raised the possibility of an up-wind effect in the Control Area that would affect X_c. Brown and Elliott (1972), in discussing the time duration of a seeded band, state: "There is some evidence that this increased duration is caused by a slowing down of the back edge of the band as it moves across the area of effect." This could affect X_{12}. Other covariates were measured

by radiosonde at Santa Barbara Airport, well into the target area, and their values may have been affected by seeding also. Because of these concerns, we have done analyses of the transformed data omitting all covariates but retaining the weights, $w_\alpha = n_\alpha$.

Table V shows results for analyses of variance for the transformed data without use of covariates. The appropriate test should be one-sided and, in each case, the regression coefficient for seeding was positive. Assessment of $t = \sqrt{F}$ leads to a one-sided significance level of 0.05 or slightly larger for each target area. While the tests are not independent, these results confirm those of the Monte Carlo assessment of the NAWC analysis of Section 2.

TABLE V

Analysis of Variance without Covariates for the Various Target Areas, Transformed Data

Target Area	Source of Variation	d.f.	Mean Squares	F-Ratio
(i)	Seeding	1	110.29	2.77
	Residual	104	39.84	-
(ii)	Seeding	1	38.57	2.84
	Residual	104	13.59	-
(iii)	Seeding	1	79.49	2.52
	Residual	104	31.55	-
(iv)	Seeding	1	100.33	2.76
	Residual	104	36.30	-
(v)	Seeding	1	73.01	2.58
	Residual	104	28.32	-

We have now highlighted what may be the major design defect in the Phase I Santa Barbara experiment, perhaps a defect that could not have been anticipated. The result has been that the covariance analyses have not been helpful, and, indeed, represent a misuse of the method, one that commonly occurs. Nevertheless, we believe that covariance analysis should be a good means to improved experimental precision. In future experiments, attention should be given to choice of good covariates measured in appropriate locations, free from the effects of seeding. Perhaps measurements at Vandenberg Air Force Base, well west of the seeding site, prior to seeding, would have been suitable.

The analyses of this section are open to minor technical concerns. The persistence effect of seeding again raises questions about the independence of experimental units. Normality assumptions are not valid for individual raingage observations but should be appropriate for target area means. Variance heterogeneity is present, but should be of little concern for analyses with transformed data. Choice of weights, $w_\alpha = n_\alpha$, for analyses with transformed data is only strictly appropriate if raingage observations are independent. Independent variables in the regression models are subject to experimental errors. While these concerns are present, we do not believe that analyses should be misleading, particularly when the transformations are used.

5. A MULTIVARIATE ANALYSIS

Somewhat in the spirit of the NAWC station-by-station analysis, but without the problem of correlated univariate tests, we have performed a crude multivariate analysis without use of covariates or transformations. We report briefly here since several problems with the multivariate approach arise.

We could not treat the response from each target area raingage as a separate response since the number of raingage stations exceeds the number of experimental units and because there would be many missing observations. Target Area (i) was divided as a

3×4 grid creating 12 subareas as defined in Table VI. In that table we show simple means $\bar{y}_s$ and $\bar{y}_{ns}$ for 50 seeded and 41 unseeded bands for each subarea, together with $\bar{n}$, the number of raingages operative on average in the subarea. Values of t are given for the univariate, two-sample Student test for subareas; one-sided significance levels vary from 0.025 to 0.149. Only 91 bands could be used because 16 bands had no operative stations in one or another of the subareas.

TABLE VI

Subareas of Target Area (i), Seeded and Unseeded Means, and Values of the Student Statistic

Latitudes		Longitudes 119.5°-120°	119°-119.5°	118.5°-119°	118°-118.5°
34°-34.41°	$\bar{n}$	2.8	8.5	16.4	21.6
	$\bar{y}_{ns}$	.214	.186	.156	.168
	$\bar{y}_s$	.285	.269	.240	.266
	t	1.14	1.45	1.58	1.74
34.41°-34.82°	$\bar{n}$	18.4	7.4	4.8	4.1
	$\bar{y}_{ns}$	.228	.182	.145	.080
	$\bar{y}_s$	.364	.285	.243	.143
	t	1.97	1.80	1.90	1.74
34.82°-35.25°	$\bar{n}$	6.2	5.6	1.5	1.6
	$\bar{y}_{ns}$	.054	.038	.042	.057
	$\bar{y}_s$	.083	.065	.075	.084
	t	1.49	1.54	1.53	1.05

The multivariate approach considers the mean response per band for each subarea as one of 12 variates and the two-sample

Hotelling test is applied with sample sizes of 50 and 41. The F-statistic associated with the test has the value 0.81 with 12 and 78 degrees of freedom and a two-sided significance level of 0.64, not indicative of a seeding effect, and less indicative of such an effect than any of the subarea Student tests, all of which have consistently positive values of t.

What has happened in the multivariate test? The sample dispersion matrix leads to correlations between subarea means of approximately 0.8, larger for subareas close together and smaller for subareas farther apart. In the computation of the Hotelling statistic, the quadratic form involved has a matrix in which all non-diagonal terms are negative and they are associated with cross-products of the variates that are always positive. Thus the quadratic form, when evaluated, has a value much reduced from the sum of its terms involving squared variate observations. The high positive correlations between subarea means have reduced greatly the effectiveness of the multivariate analysis.

There are other problems with the multivariate approach. The numbers of raingage stations operative in subareas vary from band to band and hence observation vectors are not identically distributed; in particular, they do not have a common dispersion matrix. In addition, comparison of the two sample dispersion matrices for seeded and unseeded bands shows that they are not the same at a high level of significance and the multivariate Behrens-Fisher problem arises. As in all other analyses, independence of observation vectors is suspect because of possible persistence effects of seeding.

Multivariate analysis does not appear to be a likely way to improved future experiment design and analysis. Missing observations cause great difficulty and lead to exclusion of experimental units containing good information. Only the most rigorous effort to avoid missing data could obviate the difficulty. The high correlations among subarea means would require development of special methods for efficient analysis of resulting data.

6. Additional Analyses, Remarks and Recommendations

After completion of the analyses reported above and development of a preliminary manuscript for this article, the reports of the Weather Modification Board (1978) and of its Statistical Task Force (1978) became available. The first emphasizes the national importance of weather modification and the need for much future research. The second addresses many of the statistical problems associated with such research, delineating between exploratory and confirmatory experimentation. Brillinger, Jones and Tukey, in the second report, emphasize the need for good covariates unaffected by seeding, blocking of experimental units, and the need for randomization analyses. We have regarded the Phase I Santa Barbara experiment as exploratory and parametric analyses as an appropriate and efficient approach to exploration of the data for new insights into improved future experimental design.

An opportunity for the blocking of convective bands by storms was not used in the design of the Phase I Santa Barbara experiment. The randomized decision on seeding was made for each experimental unit individually. Accordingly, the analyses of variance of Table V are appropriate if no covariates are used. But we may obtain some insights into the effects of blocking by storms and provide analyses in Table A-IV. There were 38 storms, some with only one experimental unit, some with several experimental units, all of which were either seeded or not seeded, and some with both seeded or not-seeded units. Storm effects were totally or partially confounded with seeding effect. The analyses of Table A-IV were done in such a way as to consider the additional effect of seeding after adjustments for storm effects. We see that the inclusion of storm effects in the model has increased values of R^2 and reduced residual or error variances (compare Table V with Table A-IV). But the apparent effect of seeding has disappeared again. In future similar experimentation,

use of storms for blocking should be considered, perhaps as suggested by the Statistical Task Force, with randomization of the seeding decision within storms. In the Phase II Santa Barbara experiment, a design change led to seeding or not seeding all convective bands within a storm because of concerns for a persistence effect of seeding. We plan to do randomization analyses in confirmation of indications in Tables V and A-IV, consistent with a suggestion by Gabriel elsewhere in this volume that randomization analyses might be reserved for the most critical comparisons.

In further exploratory analyses, we considered as additional sources of variation position of the band within a storm and a possible first-order carry-over effect of seeding from a seeded band to the following band if in the same storm. No real effects for positions or carry-over were found.

Some remarks and recommendations can be made after analysis of the Phase I Santa Barbara experiment. We are in near agreement with the conclusion of Elliott and Brown (1971): "Even when those bands not as receptive to seeding were included in the sample, the seeded to not-seeded precipitation increases were greater than 50%." The means of Table II show increases near to 50% and the analyses of Table IV suggest significance near to the 0.05 level.

Improved experimental design is needed but not easy to achieve. Use of convective bands as experimental units increases the number of available units per season but raises other problems. Some improvements are needed:

(i) Improved detection and determination of "seedable" bands.

(ii) More uniform dispersement of raingages over regions of interest.

(iii) Improved determination and measurement of precipitations attributed to particular convective bands.

(iv) Better determination and measurement of covariates free from possible seeding effects.

(v) Allowance for blocking by storms for further control of variation.

The quotation above supports the need for (i). Low precipitation bands in Figure 4 cause difficulty with transformations as seen in Figure 5 and these may not have been good "seedable" bands. More uniform dispersion of the raingages over the target area would be desirable, although it is understood that practical difficulties in so doing arise--many raingages used had established locations and accessability is a factor also. Better dispersion of the raingages as stated in (ii) should permit reduction of the number used. It is suspected that reading of a raingage for precipitation attributed to a given convective band is very difficult and introduces considerable experimental variability. We do not know how to effect (iii) and the difficulty is offset by the availability of more experimental units in a season when they are taken to be convective bands. The persistence effect of seeding discussed in the article is more acute with use of convective bands as experimental units.

The major design change needed in future experimentation involves the measurement of suitable covariates, covariates not subject to possible changes due to seeding (iv). It would appear to have been better to have taken the radiosonde observations at Vandenberg Air Force Base than at Santa Barbara Airport; they would then have been taken prior to seeding and hopefully unaffected by seeding. Measurement of band passage time at Vandenberg rather than at the seeding site might have been better also. The use of a control area seemed

an attractive idea but may not be feasible unless chosen to be unaffected by seeding. Further meteorological research may identify air-mass covariates more closely correlated with precipitation. Elliott, in correspondence, has suggested reasons on technical grounds for the use of non-linear functions of the available covariates and that very careful formulation of covariates is necessary if they are to be effective. While we respect his theoretical insight, models used may be regarded as first-order approximations to more complex ones. Our use of covariates reduced experimental errors; the flaw is that they seem likely to have been affected by seeding. Blocking by storms or future experiments seems feasible as suggested in (v) and likely to be helpful, particularly if blocks of unequal sizes are used as suggested by Brillinger, Tukey and Jones.

On the statistical side, transformation of the data to stabilize variances and to improve normality seems necessary. Further investigation may lead to better transforms. Multivariate methods similar to the one used in Section 5 do not seem helpful and place too stringent requirements on the experimenter. It remains to be seen if use of principal components, as considered by Scott (1978), will be helpful. In spite of the problems encountered, we believe that covariance-regression analyses, like those of Section 4, give the most potential for improved analysis of future experiments. It will be necessary to obtain good covariates, unaffected by treatment. We do not like the array of univariate tests used in Section 2 because significance is difficult to determine. Confirmation of promising analyses by randomization tests may be desirable.

APPENDIX TABLES

TABLE A-I

Correlation Coefficients among Precipitation Measures*, Covariates and Seeding, Target Area (i)

	U_1	U_2	X_c	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}
X_c	.74	.74													
X_1	.02	.05	-.01												
X_2	.38	.31	.26	.10											
X_3	-.32	-.35	-.20	.13	-.00										
X_4	.37	.36	.22	.20	.76	-.15									
X_5	-.32	-.34	-.20	.06	.07	.90	-.08								
X_6	-.12	-.14	-.01	.64	.28	.22	.26	.14							
X_7	-.10	-.11	.03	-.06	.24	.04	.04	.05	.23						
X_8	-.04	-.08	.12	-.31	.20	.11	.11	.06	.32	.35					
X_9	.38	.37	.20	.17	.73	-.25	.94	-.22	.22	.04	.09				
X_{10}	-.29	-.30	-.17	.05	.05	.87	-.06	.96	.10	.01	.04	-.19			
X_{11}	-.16	-.11	-.12	.16	.04	.02	.10	.01	.14	.18	-.14	.09	-.04		
X_{12}	.61	.65	.64	-.09	.16	-.17	.16	-.24	-.05	.10	.18	.19	-.24	-.01	
Z	.16	-	.08	.04	.02	-.10	.13	-.09	-.07	-.05	-.17	.10	-.09	.10	.16

*U_1 is the Target Area Mean, U_2 is the Target Area Mean of transformed data, Covariates are defined in (1.1), Z is the Seeding indicator variable.

TABLE A-II

Analysis of Variance Tables for Models (5)-(9)
for the Various Target Areas, Transformed Data

Model	Source of Variation	d.f.	Mean Squares (i)	Mean Squares (ii)	Mean Squares (iii)	Mean Squares (iv)	Mean Squares (v)	F-Ratios (i)	F-Ratios (ii)	F-Ratios (iii)	F-Ratios (iv)	F-Ratios (v)
(5)	Seeding	1	.57	.74	.00	.24	.46	.05	.21	.00	.02	.06
	Covariates	8	382.54	139.56	278.71	351.30	279.66	30.79	40.07	23.66	31.67	34.38
	Residual	96	12.42	3.48	11.78	11.09	8.13	-	-	-	-	-
(6)	Seeding	1	.00	.20	.28	.03	.02	.00	.03	.02	.00	.00
Without	Covariates	7	374.40	119.69	289.68	349.67	240.59	22.24	18.92	21.09	23.76	17.49
X_c	Residual	97	16.83	6.33	13.74	14.72	13.76	-	-	-	-	-
(7)	Seeding	1	11.64	3.68	7.89	10.01	4.79	.78	.92	.55	.73	.53
Without	Covariates	7	398.63	151.58	279.56	362.30	305.04	26.64	38.01	23.73	26.44	33.68
X_{12}	Residual	97	14.96	3.99	14.39	13.71	9.06	-	-	-	-	-
(8)	Seeding	1	44.68	17.04	29.59	39.51	29.52	1.46	1.51	1.23	1.43	1.28
Without	Covariates	6	200.39	54.18	164.64	188.43	120.14	6.53	4.79	6.85	6.83	5.19
X_c, X_{12}	Residual	98	30.68	11.32	24.04	27.61	23.16	-	-	-	-	-
	Seeding	1	1.56	6.29	.36	.25	11.88	.13	1.82	.03	.02	1.48
(9)	Interactions	7	16.95	3.00	15.00	14.78	8.00	1.41	.87	1.31	1.37	1.00
	Covariates	8	382.54	139.56	278.71	351.30	279.66	31.73	40.35	24.27	32.52	34.89
	Residual	89	12.06	3.46	11.48	10.80	8.02	-	-	-	-	-

TABLE A-III

Regression Coefficients for Model (5) for the Various Target Areas, Transformed Data

	Covariates	Target Areas				
		(i)	(ii)	(iii)	(iv)	(v)
Constant		.8952	1.6289	.8241	.8758	1.5273
X_c	Control Area	1.6467**	2.6051**	1.3451**	1.5419**	2.4728**
X_2	700 mb Spd.	.0136**	.0105**	.0161**	.0140**	.0103**
X_3	700 mb Wind Dir.	-.0040**	-.0038**	-.0047**	-.0042**	-.0040*
X_6	500 mb Temp.	-.0077	.0082	-.0143	-.0084	.0029
X_7	Stab. Class	-.1327*	-.1249	-.1593*	-.1383*	-.1258
X_8	Showalter Index	-.0326*	-.0402**	-.0336*	-.0319*	-.0370**
X_{11}	Instab. Transpt.	-.0001	.0000	-.0002	-.0001	.0000
X_{12}	Duration	.0042**	.0037**	.0051**	.0043**	.0034**
Z	Seeding	.0164	.0373	.0008	.0111	.0200

*Significant at level 0.05. **Significant at level 0.01.

TABLE A-IV

Analysis of Variance Tables for the Various Target Areas, Storms as Blocks, Transformed Data

Source of Variation	d.f.	Mean Squares, Target Areas (i)	(ii)	(iii)	(iv)	(v)	F-Ratios, Target Areas (i)	(ii)	(iii)	(iv)	(v)
Seeding	1	23.97	12.57	12.57	19.80	21.15	0.82	1.14	0.57	0.75	0.95
Storms	37	61.08	18.86	50.66	56.68	40.75	2.08	1.70	2.30	2.16	1.83
Residual	67	29.39	11.07	21.99	26.25	22.24	-	-	-	-	-
R^2		-	-	-	-	-	0.54	0.49	0.56	0.55	0.51

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SUPPLEMENTARY APPENDIX

Appendix Table A-III of the article shows the regression coefficients for Model (5) of (4.5) for the transformed data for the five target areas. Tables SA-I to SA-IV of this Supplementary Appendix below give the regression coefficients for Models (6) to (8) of (4.5).

Blocking of convective bands (experimental units) by storms is discussed in Section 6 of the article and analyses of variance are given in Table A-IV. The model used is

$$y_{i\alpha} = \mu + Z_{i\alpha} + St_i + \epsilon_{i\alpha}, \quad \alpha = 1,\ldots,m_i, \quad i = 1,\ldots,S, \tag{SA1}$$

where $y_{i\alpha}$ is the mean of the transformed precipitation responses for band α of storm i for a specified target area, $Z_{i\alpha} = 1$ or 0 as band α of storm i was or was not seeded, St_i is the effect of storm i, μ is a general mean, and $\epsilon_{i\alpha}$ is the residual error for band α of storm i, taken in the parametric model to have variance $\sigma^2/n_{i\alpha}$, where $n_{i\alpha}$ is the number of raingage observations included in the computation of $y_{i\alpha}$. For some storms, $m_i = 1$ and there is confounding between the storm effect and the seeding variable, as also occurs when all values of $Z_{i\alpha}$ are either one or zero for a storm. The analysis of variance for a target area was done through minimization of

$$\sum_i \sum_\alpha n_{i\alpha}(y_{i\alpha} - \mu - Z_{i\alpha} - St_i)^2 \tag{SA2}$$

under a linear constraint on storm effect parameters St_i for determinancy. In Table A-IV, the sums of squares shown for seeding were computed as the additional reduction in the sum of squares (SA2) obtained through inclusion of $Z_{i\alpha}$ in the model.

Reference is made also in Section 6 of the article to consideration of position of a band within a storm and a possible first-order carry-over effect of seeding from a seeded band to the following band if in the same storm. Since bands are not of equal duration nor equally spaced within a storm, the modelling is necessarily somewhat crude. The full model representation, extending model (SA1) above, has

$$y_{i\alpha} = \mu + Z_{i\alpha} + St_i + \delta^k_{i\alpha} P_k + \gamma_{i\alpha} L + \epsilon_{i\alpha}, \qquad \text{(SA3)}$$

where the new parameters are defined as follows: $\delta^k_{i\alpha} = 1$ or 0 as band α of storm i is or is not in position k of the sequence of bands within the storm, P_k is the effect of position k, $\gamma_{i\alpha} = 1$ or 0 as there does or does not exist a seeded band immediately preceding band α in the same storm i, and L is the carry-over effect of seeding from the preceding band. Various analyses for Target Areas (i) to (iv) were done with Model (SA3) complete or with some terms omitted; Target Area (v) was not included in this work. These analyses are given in Tables SA-V to SA-IX. For a given analysis of variance model terms were included in a sequence ascending in the list of sources of variation, that is, seeding was always added last to obtain the additional reduction in the sum of squares due to seeding. Note that the effects of positions and carry-over from preceding seeding were negligible in all analysis of variance tables.

TABLE SA-I

Regression Coefficients for Model (6) for the Various
Target Areas, Transformed Data

Covariates		Target Areas				
		(i)	(ii)	(iii)	(iv)	(v)
Constant		1.0406*	1.9044**	.9403	1.0173*	1.7442**
X_2	700 mb Spd.	.0185**	.0181**	.0200**	.0185**	.0195**
X_3	700 mb Wind Dir.	-.0049**	-.0053**	-.0053**	-.0050**	-.0051**
X_6	500 mb Temp.	-.0064	.0104	-.0132	-.0071	.0084
X_7	Stab. Class	-.1462*	-.1501	-.1690	-.1503*	-.1574
X_8	Showalter Index	-.0355*	-.0439*	-.0361	-.0347*	-.0442*
X_{11}	Instab. Transpt.	-.0003	-.0002	-.0003	-.0003	-.0003
X_{12}	Duration	.0075**	.0090**	.0078**	.0075**	.0084**
Z	Seeding	-.0003	.0194	-.0138	-.0040	.0036

*Significant at level 0.05. **Significant at level 0.01.

TABLE SA-II

Regression Coefficients for Model (7) for the Various Target Areas, Transformed Data

	Covariates	Target Areas				
		(i)	(ii)	(iii)	(iv)	(v)
Constant		1.0224*	1.7110**	.9967	1.0094*	1.6294**
X_C	Control Area	2.4294**	3.3010**	2.3017**	2.3573**	3.1060**
X_2	700 mb Spd.	.0130**	.0102*	.0153**	.0134**	.0094*
X_3	700 mb Wind Dir.	-.0044**	-.0041**	-.0051**	-.0045**	-.0044**
X_6	500 mb Temp.	-.0128	.0029	-.0199	-.0135	-.0025
X_7	Stab. Class	-.1226	-.1148	-.1456	-.1265	-.1166
X_8	Showalter Index	-.0218	-.0306*	-.0204	-.0207	-.0272
X_{11}	Instab. Transpt.	-.0001	.0001	-.0001	-.0000	.0001
Z	Seeding	.0731	.0825	.0725	.0700	.0637

*Significant at level 0.05. **Significant at level 0.01.

TABLE SA-III

Regression Coefficients for Model (8) for the Various Target Areas, Transformed Data

Covariates	Target Areas				
	(i)	(ii)	(iii)	(iv)	(v)
Constant	1.6166*	2.5115**	1.5801*	1.6099*	2.3588**
X_2 700 mb Spd.	.0235**	.0246**	.0250**	.0235**	.0254**
X_3 700 mb Wind Dir.	-.0070**	-.0078**	-.0076**	-.0071**	-.0075**
X_6 500 mb Temp.	-.0194	-.0078	-.0251	-.0195	-.0075
X_7 Stab. Class	-.1354	-.1366	-.1519	-.1354	-.1530
X_8 Showalter Index	-.0076	-.0104	-.0074	-.0071	-.0129
X_{11} Instab. Transpt.	-.0003	-.0002	-.0003	-.0002	-.0002
Z Seeding	.1428	.1771	.1399	.1387	.1576

*Significant at level 0.05. **Significant at level 0.01.

TABLE SA-IV

Regression Coefficients for Model (9) for the Various Target Areas, Transformed Data

Covariates		Target Areas (i)	(ii)	(iii)	(iv)	(v)
Constant		.7664	1.0349	.9381	.8311	.9543
X_C	Control Area	1.8542**	2.8295**	1.5487**	1.7384**	2.6603**
X_2	700 mb Spd.	.0051	.0023	.0071	.0057	.0028
X_3	700 mb Wind Dir.	-.0034	-.0017	-.0049*	-.0038	-.0018
X_6	500 mb Temp.	-.0128	.0007	-.0186	-.0126	-.0021
X_7	Stab. Class	-.1274	-.0494	-.1752	-.1309	-.1291
X_8	Showalter Index	-.0050	-.0282	.0004	-.0053	-.0154
X_{11}	Instab. Transpt.	-.0002	.0001	-.0003	-.0002	.0001
X_{12}	Duration	.0046**	.0042**	.0054**	.0047**	.0044**
X_2Z		.0123	.0110	.0132	.0121	.0102
X_3Z		-.0009	-.0037	.0006	-.0004	-.0040
X_6Z		.0102	.0156	.0082	.0080	.0111
X_7Z		-.0262	-.1441	.0141	-.0247	-.0207
X_8Z		-.0585*	-.0322	-.0701*	-.0566*	-.0472
$X_{11}Z$		.0001	-.0002	.0003	.0002	-.0002
$X_{12}Z$		-.0012	-.0015	-.0009	-.0009	-.0021
Z	Seeding	.3212	1.2888	-.1867	.1324	1.2021

*Significant at level 0.05. **Significant at level 0.01.

TABLE SA-V

Analysis of Variance Tables for the Various Target Areas, Transformed Data, Seeding and Position Effects

Source of Variation	d.f.	Mean Squares Target Areas (i)	(ii)	(iii)	(iv)	F-Ratios Target Areas (i)	(ii)	(iii)	(iv)
Seeding	1	82.97	29.96	58.91	75.37	1.98	2.10	1.77	1.97
Positions	6	9.76	4.12	7.34	9.30	0.23	0.29	0.22	0.24
Residual	98	41.96	14.25	33.24	38.21	--	--	--	--
R^2		--	--	--	--	0.03	0.04	0.03	0.03

TABLE SA-VI

Analysis of Variance Tables for the Various Target Areas Transformed Data. Seeding and Carry-Over Effects

Source of Variation	d.f.	Mean Squares Target Areas (i)	(ii)	(iii)	(iv)	F-Ratios Target Areas (i)	(ii)	(iii)	(iv)
Seeding	1	98.66	28.41	77.09	90.48	2.45	2.08	2.42	2.47
Carry-Over	1	12.65	18.62	2.70	10.57	0.32	1.37	0.09	0.29
Residual	103	40.22	13.64	31.85	36.65	--	--	--	--
R^2		--	--	--	--	0.03	0.03	0.02	0.03

TABLE SA-VII

Analysis of Variance for the Various Target Areas
Transformed Data, Seeding, Storm and Position Effects

Source of Variation	d.f.	Mean Squares Target Areas (i)	(ii)	(iii)	(iv)	F-Ratios Target Areas (i)	(ii)	(iii)	(iv)
Seeding	1	28.10	11.97	16.60	23.12	0.89	1.00	0.70	0.82
Positions	6	7.18	2.45	5.54	6.26	0.23	0.21	0.23	0.22
Storms	37	61.08	18.86	50.66	56.68	1.94	1.58	2.15	2.12
Residual	61	31.51	11.92	23.55	28.16	--	--	--	--
R^2		--	--	--	--	0.55	0.50	0.57	0.56

TABLE SA-VIII

Analysis of Variance for the Various Target Areas
Transformed Data, Seeding, Storm and Carry-Over Effects

		Mean Squares Target Areas				F-Ratios Target Areas			
Source of Variation	d.f.	(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
Seeding	1	10.07	4.33	4.93	7.67	0.34	0.40	0.22	0.29
Carry-Over	1	30.33	21.49	17.46	28.27	1.03	1.95	0.79	1.07
Storms	37	61.08	18.86	50.66	56.68	2.06	1.71	2.28	2.15
Residual	66	29.59	11.03	22.18	26.40	--	--	--	--
R^2		--	--	--	--	0.54	0.50	0.56	0.55

TABLE SA-IX

Analysis of Variance for the Various Target Areas
Transformed Data, Seeding, Storm, Carry-Over, and Position Effects

Source of Variation	d.f.	Mean Squares Target Areas				F-Ratios Target Areas			
		(i)	(ii)	(iii)	(iv)	(i)	(ii)	(iii)	(iv)
Seeding	1	3.54	0.56	2.18	2.64	0.11	0.05	0.92	0.09
Positions	6	10.84	3.95	7.73	9.08	0.34	0.34	0.33	0.32
Carry-Over	1	30.33	21.50	17.46	28.27	0.96	1.86	0.74	1.00
Storms	37	61.08	18.86	50.66	56.68	1.94	1.60	2.14	2.01
Residual	60	31.57	11.80	23.67	28.22	--	--	--	--
R^2		--	--	--	--	0.56	0.51	0.58	0.51

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20. ABSTRACT

Data from a weather modification experiment are examined and a number of statistical analyses reported. The validity of earlier inferences is studied as are the utilities of various statistical methods. The experiment is described. The original analysis of North American Weather Consultants, who conducted the experiment, is reviewed. Data summarization is reported. A major approach to analysis is through the use of cloud-physics covariates in regression analyses. Finally, a multivariate analysis is discussed. It appears that the covariates may have been affected by treatment (cloud seeding) and that their use is invalid, not only reducing error variances but removing treatment effect. Some recommendations for improved design of similar future experiments are given in a concluding section, including preliminary trial use of blocking by storms.